# Performance Measurement in C2 Systems

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**Abstract**

The continuous transformation of the US military into an integrated and a dominant "full spectrum" capability requires a comprehensive and evolutionary system model (the objective) and a prescribed set of transformation processes (the means) whose incremental results are measurable against operational requirements. Given its sheer size and complexity, this military system must be partitioned into logical and semi-independent elements. The individual and ensemble performance of system elements must be objectively measured, and characterized by specific and reusable metrics. Taken together, the system model and the classes of metrics define a *performance measurement framework* (PMF). This paper outlines the design of a generalized and scalable performance measurement framework for the Navy's FORCEnet environment.

**Keywords**: System Performance, Metrics, System Models, Cybernetics, Command and Control

## 1. INTRODUCTION

Within the context of military transformation, end-to-end performance measurement of command and control (C2) applications in "network centric warfare" environments represents a specific and challenging subtask. Primary challenges derive from the iterative and spiral nature of long-term development programs and the inherent performance anomalies found in distributed large-scale enterprises. [3] These challenges notwithstanding, a practical means of specifying and measuring the behavior of DOD C2 applications is required for 1) establishing initial system and application design criteria, 2) specifying realistic operational baselines, 3) defining and running system operations and maintenance diagnostic processes, and 4) maintaining reusable and scalable sets of metrics that effectively support historical records that underlie continuous system and process improvements.

In general, command and control environments are complex, involving chains of command (i.e., accountability hierarchies) and joint forces (i.e., distributed peer-level organizations) that evolve in their structure, missions and objectives over time. This two dimensional context provides many sources of ambiguity in both time and space. In order to define performance metrics and associated methods for making consequential and reproducible measurements, a scalable and extensible model of C2 enterprise dynamics is required.

The DOD transformation objectives are represented by a five tier pyramid model [5, 6, 8, 9, and 10] with a grid-computing foundation and "full spectrum dominance" at the apex. The grid hosts network-centric warfare capabilities that, at the intermediary levels, support "information superiority" and "decision superiority." Discussion of transformation objectives generally refers to levels of warfare. [1, 7]

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**Strategic level** of war is divided into two sublevels: strategic national (SN) and strategic theater (ST). At this level, a nation, often as a member of a group of nations, determines national or multinational (alliance or coalition) security objectives and guidance, and develops and uses national resources to accomplish these objectives. Activities at this level establish national and multinational military objectives; sequence initiatives; define limits and assess risks for the use of military and other instruments of national power; develop global plans or theater war plans to achieve these objectives; and provide military forces and other capabilities in accordance with strategic plans. In the [12], this level of war is divided into strategic-national (DOD/Service/interagency) and strategic-theater (combatant command) to provide clarity and focus for task development and execution.

**Operational level** of war is where campaigns and major operations are planned, conducted, and sustained to accomplish strategic objectives within theaters or areas of operations. Activities at this level link tactics and strategy by establishing operational objectives needed to accomplish the strategic objectives, sequencing events to achieve the operational objectives, initiating actions, and applying resources to bring about and sustain these events. These activities imply a broader dimension of time or space than do tactics; they ensure the logistic and administrative support of tactical forces and provide the means by which tactical successes are exploited to achieve strategic objectives.

**Tactical level** of war is where battles and engagements are planned and executed to accomplish military objectives assigned to tactical units or task forces. Activities at this level focus on the ordered arrangement and maneuver of combat elements in relation to each other and to the enemy to achieve combat objectives.

In terms of levels of war, the DON has formulated “joint and naval performance measures” to support its transformation. [12] Performance measures previously defined for joint and naval operations contain some 755 specific performance categories – 218 at the strategic level, 216 at the operational level, and 321 tactical level measurements. The Navy’s current Sea Trials activity focuses on the tactical environment.

The FORCEnet (Fn) program is the catalyst for transforming the US Navy into a “fully netted force” capable of engaging “widely distributed combat power and command with increased awareness and speed as an integral part of the joint team.” [7] The roadmap specifically calls for three major phases of development and deployment: “Spiral 1” (Figure 1) from FY02-07, “Spiral 2” from FY07-10 and “Spiral 3 from FY10-20. Spiral 1 comprises a set of requirements and processes for system experiments, initiatives and acquisitions providing immediate combat capabilities. Spiral 2 comprises activities designed to meet “compelling” future naval challenges in the FY07-10 timeframe, taking into consideration the FY04-10 science and technology (S&T) and research and development (R&D) roadmaps. And Spiral 3 is aimed at creating an “enduring asymmetric advantage” for the Navy of FY10-20, coordinated with the primary platform modernizations and their associated requirements.

A performance measurement framework that is applicable to these three development periods requires 1) a generalized model of distributed real-time command and control systems, 2) the FORCEnet objectives cast within this distributed C2 model, and 3) a reusable and extensible set of strategic, operational and tactical performance metrics and measurement processes that capture the essential behaviors of deployed C2 applications.

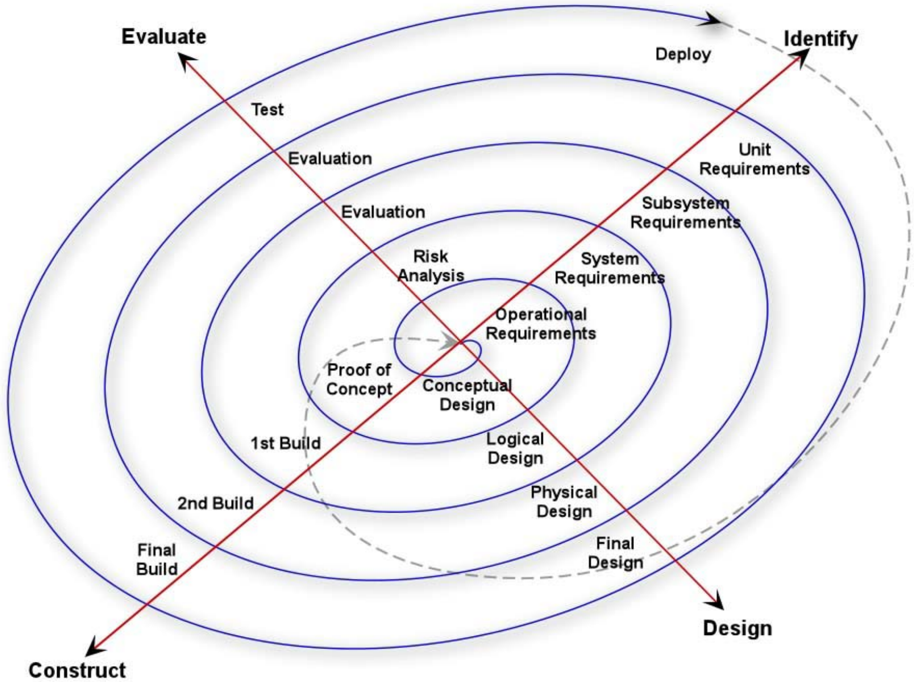


**Figure 1 - Spiral Development Process**

## 2. C2 Systems Model

Major Scott F. Murray, US Air Force, in his 2002 article *Battle Command, Decisionmaking and the Battlefield Panopticon* [13], quotes Elting Morrison's conclusion that "the primary impediment to exploiting new technologies in the military is the cultural impact of organizational change." This conclusion is not unique to the military. It is endemic to medium to large scale bureaucracies, regardless of whether they exist in commercial, government or institutional settings. Given the special (e.g., large and lethal) nature of the military command and control environment, the point is especially relevant. As a consequence, the nature of organization and the process of command and control within that organization are critical to the success of transformation activities.

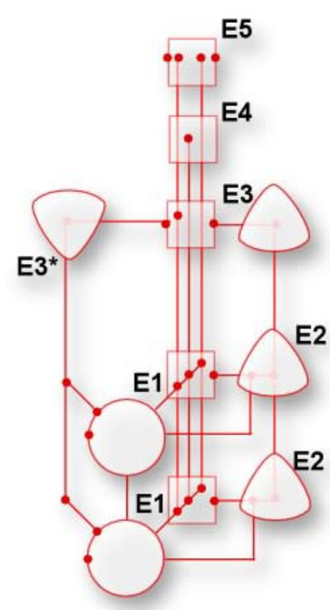


**Figure 2 - Echelons of Control**

Figure 2 illustrates the PMF C2 systems model. The model defines five *echelons* of control, as defined in cybernetics and developed from models of human neuro-anatomy.[3] At the highest level, echelon 5 (E5) defines a system's supervisory control, its identity, purpose and vision (doctrine) – the basis for strategy and action – where the context for its perceptions (belief system) and behaviors (prerogatives) takes form. For the Department of the Navy, E5 represents the CNO. Echelon 4 (E4) provides innovation, development and planning

functions, whereby the state of the external and internal worlds are rationalized and incorporated into the forward-looking strategies for guiding the system's adaptation and evolution. Applied to the US Navy, E4 is represented in part by the CNO N6 directorate. Echelon 3 (E3) is operationally focused, as through the Navy's XOs, providing the function of supervision through audit (i.e., parasympathetic, E3*) and delegation (i.e., sympathetic or autonomic control) of lower level processes. Echelon 2 (E2) provides the per-process regulatory controls, providing synchronization and conflict resolution (i.e., local sympathetic) behavior of the individual processes that share resources and missions. And, where the real work of the enterprise is carried out, echelon 1 (E1) contains the logic and machinery of the individual processes, along with their interfaces to the embedded lower level services on which they in turn depend.

Viable systems are embedded in operational environments, where external realities dictate conditions for action and survival. This external environment (Figure 3) defines the dynamic political, social and battle contexts within which the viability of the system – and hence the critical success factors (measures of performance) that govern good decision making – takes place. Within these external contexts a system may be proactive, and it must certainly be reactive.

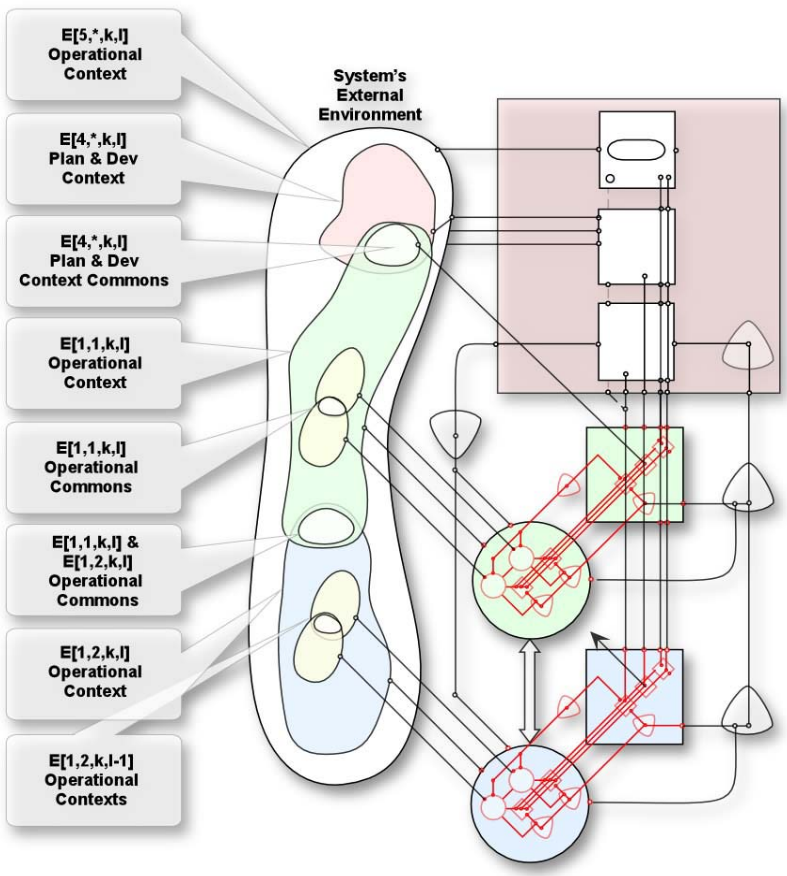


**Figure 3 - Operational Contexts**

A system's viability, therefore, must take into consideration measures of both internal states and external state. The timely correlation of these measurements, and the world view this correlation provides, defines the basis for analysis and subsequent action. Clearly, correlated measurements that arrive too early or too late have less value to the E3, E4 and E5 control functions than correlated measures that arrive "just in time" (JIT). Viable C2 systems must therefore be sensitive to the value of time critical measures – in short, a C2 system is a real-time distributed system – in all of its technical meaning.

As diagrammed in Figure 3 each E1 "production process," at the next lower level, may be recursively represented by a control structure similar to Figure 2. Applying the model to the DOD, the top level system model might be drawn as in Figure 4, where the core E1 processes include the CJCS/JCS/Staff, the Joint Combat Commanders, and the Navy, Marine Corps, Air Force, and Army forces. E5 here is the OSD, E4 the ASD and its technical support directorates, and so on.

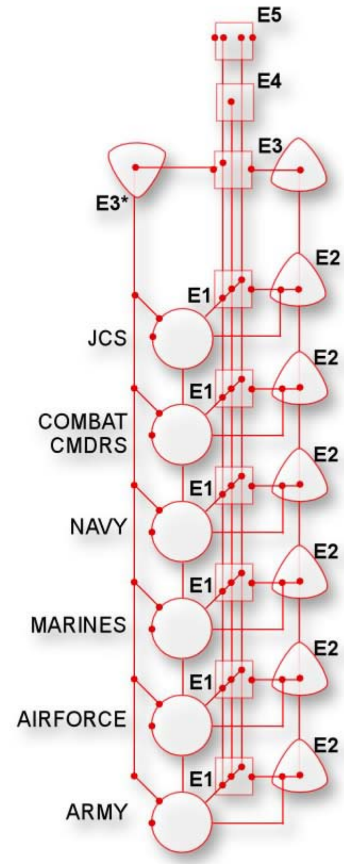


**Figure 4 - SECDEF Control Domains**

For the purpose of developing a unified and scalable performance measurement framework, the system model is applied recursively to the six E1 processes of Figure 4, respectively, to identify their individual operational structures. The number of recursions is equal to the number of desired levels of C2 behavior one wishes to observe (measure). In practice, six levels have been shown sufficient to identify the essential behavior of large enterprises. In the commercial world [3] these levels translate into multi-domestic Corporations (L5), Business Areas (aka "Division," L4), Business Units (L3), Production Plants (L2), Production Processes (L1), and Production Units (aka "Intelligent Devices," L0). The military equivalent has yet to be firmly established and exploited, but for the purposes of this work we believe that the six-level cybernetic model is also adequate. Clearly, the PMF requires some form of system reference model, one that specifies an appropriate level of functional detail, but one that does not cause such complexity that it obscures the value of performance measurement. [14]

Figure 5 expands Figure 4's E1 Navy process into four additional levels. This particular "view" of the Navy's organization begins with the SECDEF at the top and ends at the lowest level with, in this case, a particular naval vessel within a battle group. The nesting could go down to the level of a piece of automated equipment on the vessel (e.g., a semi-automatic "intelligent weapon"), and up to the Commander in Chief (POTUS). In the PMF the number of levels shall be determined by the focus of the measurement program and the desired granularity, accuracy and inter-relationships among the metrics required for analyzing effectiveness of selected C2 policies and mechanisms. In this regard, the model is highly scalable.

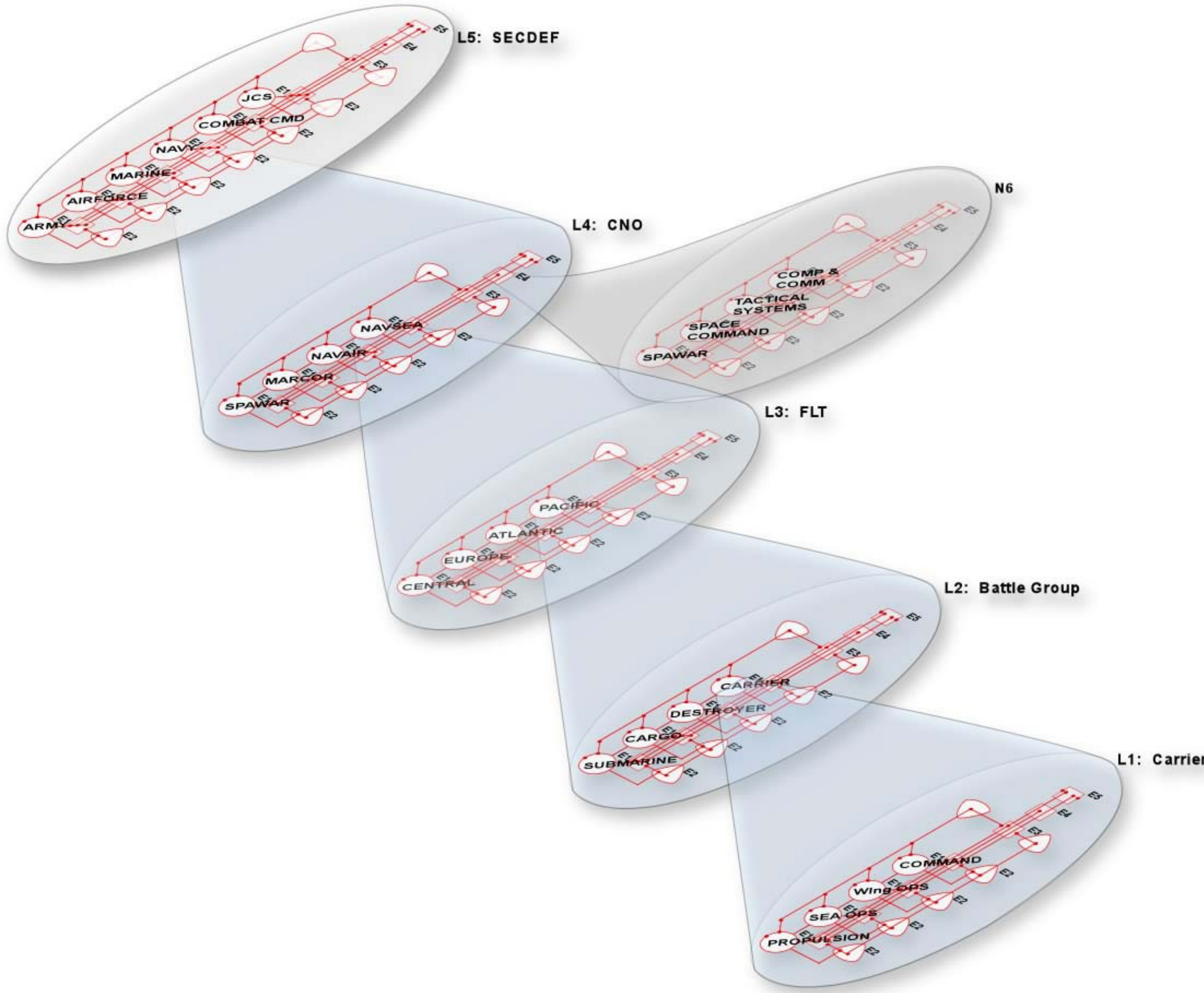


**Figure 5 - Navy C2 Command Levels**

Figure 5 follows a given path (or "thread") of operational command authority appropriate for defining the performance of a battle group within fleet operations. In this situation, the PMF might be configured to provide real-time metrics for characterizing the behavior of a carrier within a battle group as that group operates within a time critical fleet asset management scenario. What is not depicted here, and which may indeed be more critical, is the behavior of that same carrier within the purview of the Combat Commanders responsible for a tactical military action requiring the carrier's assets (e.g., assault support). Such a view would require the PMF to change "focus," moving to a different aspect of the command structure, this time with CNO replaced by the Combat Commander(s) and the FLT replaced by the Joint Force Commands.

The PMF must therefore provide a means of (re)focusing the measurement system dynamically, much as an astronomer repositions and refocuses a telescope. In fact, the relative performance of any given set of Naval assets may well be the convolution or ensemble average of the performance of that element as seen through several such views, with appropriate weighting being dependent on battlespace situation, time of day, BDA, etc. Important design criteria for the PMF include this user

interface, its controls, its fidelity, and its ability to define appropriate foci for time-critical measurements and measurement processes. The PMF user interface is the subject of a specific R&D proposal presented elsewhere.

## 3. Performance Metrics

As noted, the PMF is required to be a *real-time system*, meaning that metrics – whether strategic, operational or tactical – must carry along with their acquired "values" the time the measurements were made (i.e., a time-stamp), and some measure of the "quality" of those values at that time. For reasons of computing causal relationships among measurement events, time stamps must be in absolute time (e.g., UTC/GPS). The quality parameter(s) associated with this measurement must define the status of the sensors in terms of their ability to render specific degrees (ranges) of accuracy and precision – the fidelity issue.

A system is real-time to the degree that its correct behavior requires adherence to certain completion-time semantics (i.e., its ability to meet time constraints and the predictability of meeting deadlines). [11] A distributed system is real-time to the degree that transnode computations (aka, distributed threads) have predictable timing as they flow through the interconnecting grid. This requires that network latencies be bounded and known *a priori* by their probability distribution functions. Parenthetically, it is noted that the current level of effort being expended in the NMCI program [15] does not formally address the complex technical issues of end-to-end timeliness in the naval intranet, the associated service level agreements (SLA) supporting such qualities-of-service (QoS), nor the "costs" of missing the timeliness "guarantees" that C2 applications might incur in the face of failed, late, or corrupted "transnode threads."

The quality of any given C2 application, and the ultimate utility of the PMF, is dependent on the capability of the sensors that make the measurements at each level, the timeliness of the transport system that delivers the payload containing the measurement, the ability of the receiving sensory perception process that filters or correlates the measurement, and so on.

The PMF defines a measurement as:

```
measurement_id :=   {command_level,
                     control_echelon,
                     sensor_id,
                     sensor_value,
                     sensor_timestamp,
                     sensor_quality}
```

For each critical metric defined in [2] and [12] the PMF assigns and registers unique measurement identifications (MID).

Figure 6 depicts a three dimensional *measurement id space*, bounded in depth by six levels of control, vertically by five echelons of system regulation, and horizontally by the three classes of measurements – strategic, operational and tactical – over 750 in all. The figure also depicts two representative measurement *sets*, S1 and S2.

An important goal of the PMF is to answer questions such as "what effects does the performance of a L2 operational commander (i.e., C2 application set S1) have on the performance of a tactical commander at L1 (i.e., C2 application set S2)?" While the figure does not answer such questions, it provides a degree of clarity as to the dimensions (e.g., vector lengths) of the issues. It also introduces the notion of "measurement sets" and their importance in quantifying the essential performance parameters for given C2 situations.

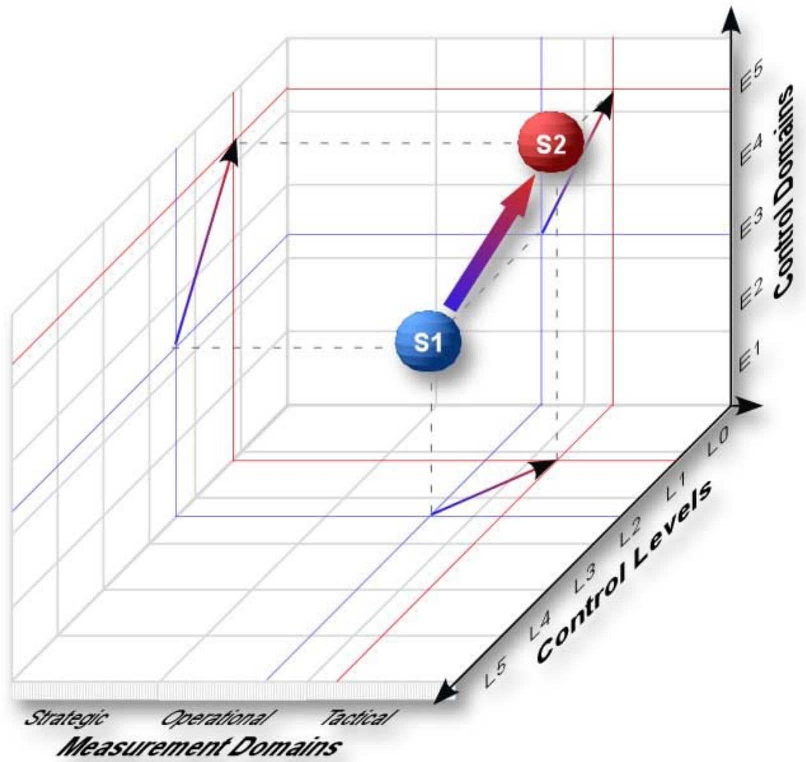


**Figure 6 - 3D Measurement ID Space**

The current phase of the PMF development effort focuses on the lowest (tactical) group, albeit the one with the highest data rate and number of measurements categories – over 300 are defined in [12] for this group. Each measurement category in this group contains an average of over 5 metrics (e.g., speed, distance, percentage, completions, events, etc.). Given the model chosen, the measurement space for this tactical group contains well over 10,000 possible metrics (300 x 5 x 6 x 5), the relevant subsets being functions of the level of granularity (specificity) required and the focus of C2 performance monitoring objectives.

Any data set of that size would be difficult to interpret if it were time invariant. By the nature of evolving battle conditions and the stochastic character of network transport (e.g., the QoS issues mentioned above in the NMCI alone), the measurement space is clearly time-varying. In fact, it likely to be discovered that the space contains processes that are neither stationary nor ergodic – an analysis that will have to await the deployment of the PMF measurement "probes" and the evaluation of the results of several measurement sets from different applications and over different time periods.

As partial compensation for the numerical complexity and end-to-end performance uncertainties expected in measurement statistics, the PMF defines several generalized basis measures that apply equally well across all command levels. These measures are "unit-less," with their relationships defined below in Figure 7. These "basis metrics" are derived from the operation of the echelon controllers.

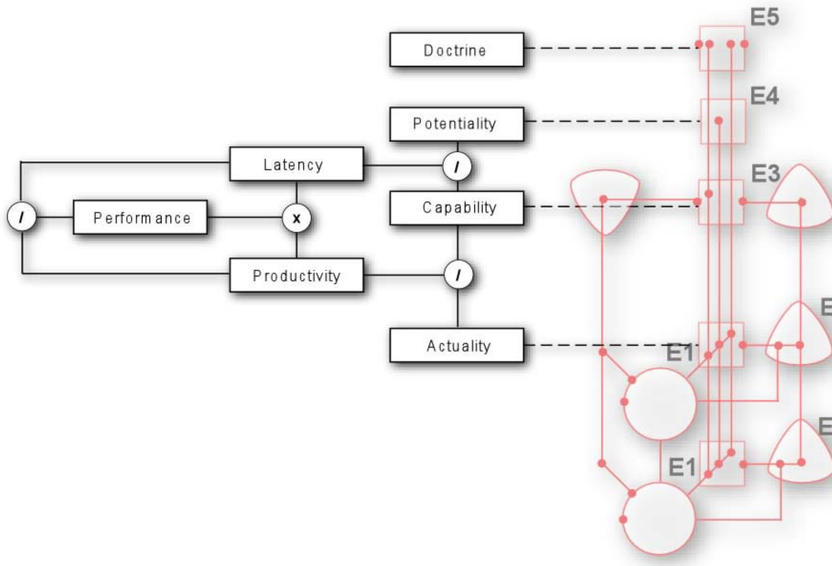


**Figure 7 - Generalized "Basis" Metrics**

1. Potential ............The design potential or constraints of a given C2 function, determined by its architecture.
2. Capability..........The [allocated or funded] level of capacity of a given C2 function.
3. Actuality............The current level of actual measured performance of a given C2 function.
4. Latency..............The ratio of capability to potential – representing the [as yet unallocated] capacity available within a given design.
5. Potential ............The ratio of actuality to capability – the [remaining or allocatable] "headroom" available without altering the design potential (i.e., allocatable or fundable capacity).
6. Performance ......The ratio of actuality to potential – the present efficiency of a system relative to its design.

Given the recursive nature of the system model, these generalized measures are produced at each level of C2 hierarchy, providing a means of comparing and accumulating the performance of the embedded systems and their associated effects on the performance of the C2 environments within which they operate.

## 4. PERFORMANCE MEASUREMENTS

The process of taking and analyzing performance measurements is the subject of a separate paper. For the purpose of this introduction, the PMF methodology recognizes that commands from Level 0 "intelligent" devices through Level 5 senior officers all produce meaningful and relevant measures of performance. As such, functioning elements at each level require sensors that collect and transmit performance data. These sensors (servers) and the effectors they feed (clients) are in addition to those sensors and effectors that carry out the war fighting mission itself. The PMF is therefore a "metasystem" within which the combat systems operate and are evaluated. The measurement processes must therefore be able to "monitor" both classes of end-systems, both mission *assets* and mission *infrastructure*.

The PMF recognizes both classes of end system in the grid-based environment defined by FORCEnet and its containing Unified Command System (UCS) [7, 8, and 16]. The PMF mechanisms planned for identifying and measuring performance are based on the concept of both synchronous and asynchronous probes (aka, threads or intelligent agents) that traverse the grid to evaluate sensor state (quality), make measurements (value), and time-stamp the events at end-system elements engaged in C2 applications of interest. In doing so they also assess the end-to-end transit times that contribute to overall performance. In addition, PMF measurement agents are dispatched to various network nodes within the grid environment to act as diagnostic servers. The particular design, deployment and management of these probes and the databases that result from their operation will be the subject of a subsequent paper.

## 5. Conclusions

We have presented the general characteristics of the design and specification of a performance measure framework for C2 application in a network-centric military environment. The PMF is based on a recursive system model that recognizes five control elements. The recursion depth is determined by the number of command levels to be considered. The measurements to be used by the PMF include those strategic, operational and tactical metrics identified by the DON in its assessment of core requirements, and a set of generalized measures that apply to all command levels.

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